Filtering to Meet DSN Requirements at High Data Rates

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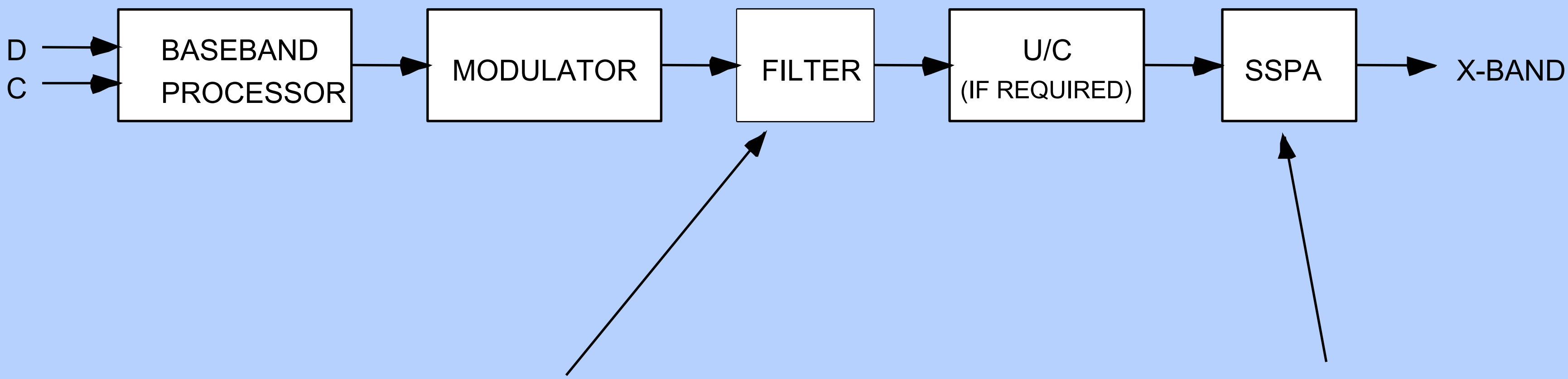
History

- Historical spacecraft transmitter topology and filtering have been oriented toward emission control without regard for the effect of filtering on Intersymbol Interference (ISI).
- The topology used often causes spectral regrowth such that emission requirements are not met and creates AM/AM and AM/PM degradations.



- Geometric Symmetrical Filter
- No Group Delay Equalization
- Causes Envelope Variations
- Filter Shape Not Designed To Minimize ISI
- Heavy Filtering At High Data Rates

- Amplifier Operating Point At The Verge Of Compression

Figure 1. Historical Transmitter Topology

Consequences Of The Classical Transmitter Topology and Filtering At High Data Rates (>300Mb/s)

- Heavy filtering causes significant envelope variations ~ 3-4dB.
- Filter shape, symmetry, group delay, etc. greatly distorts the eye diagram of the data and causes significant intersymbol interference.
- The envelope variations cause significant AM/AM and AM/PM on the output signal from the nonlinear SSPA.
- The nonlinear operation of the SSPA with the varying input envelope restores sidebands such that emission requirements are not met (have measured as much as 30 dB of sideband restoration).
- The nonlinear operation of the SSPA with the varying input causes further distortion of the data eye diagram.

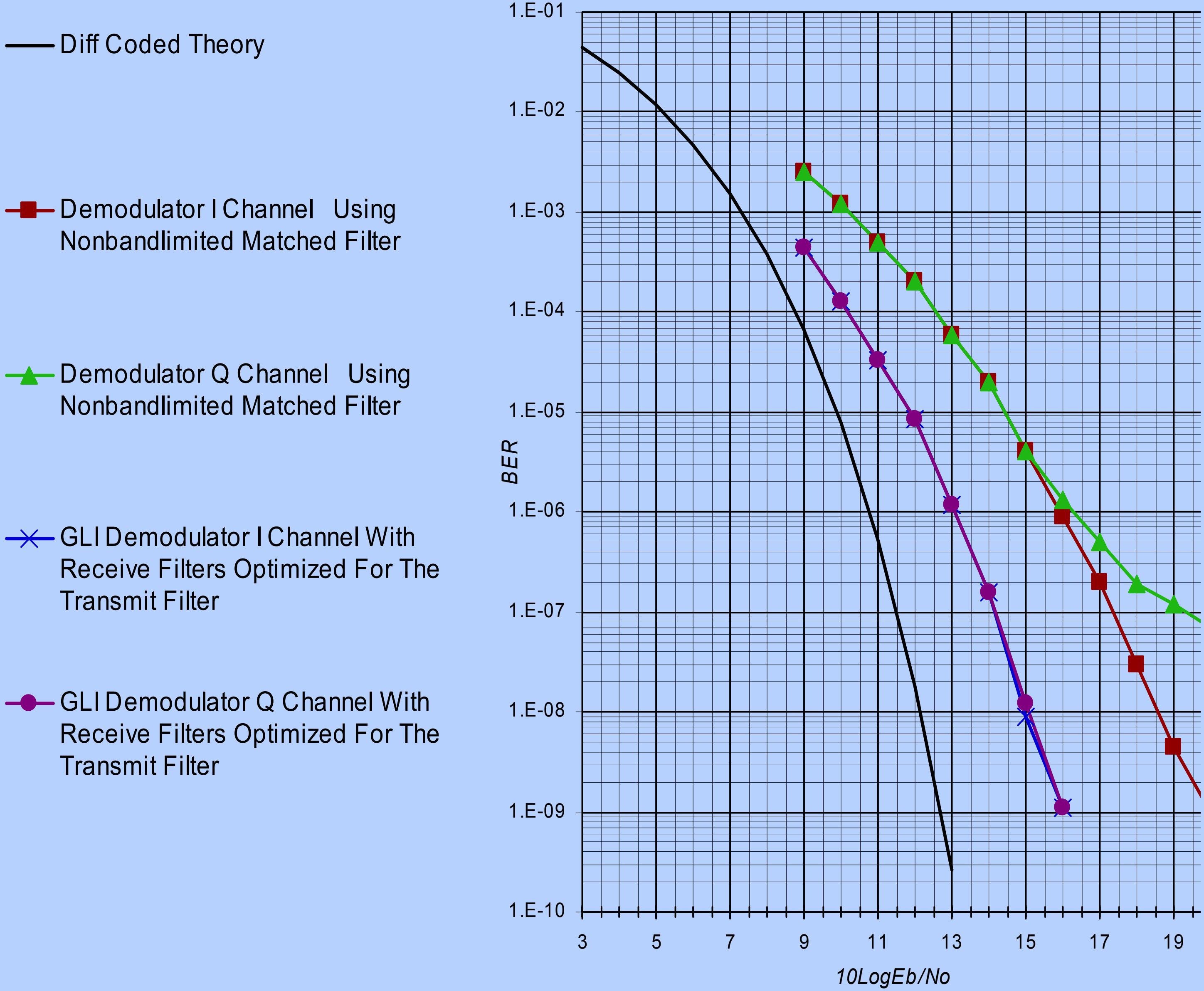


Figure 2. Actual High Data Rate System Using The Historical Topology and Filtering

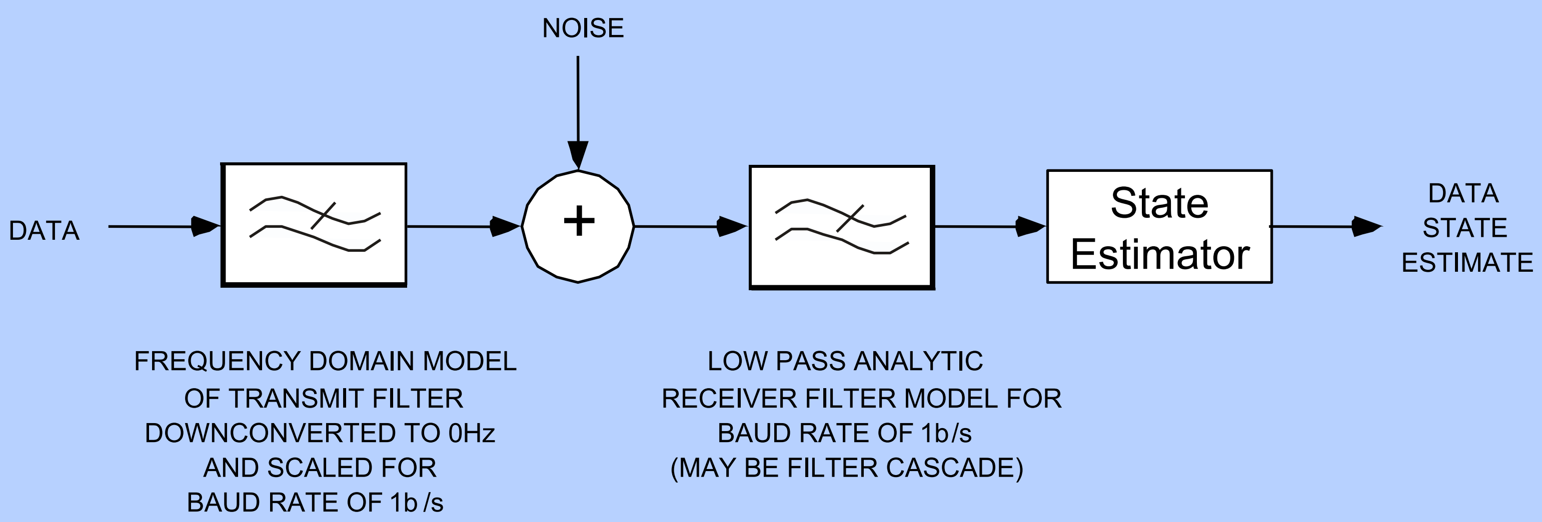


Figure 3. Block Diagram Of Optimization Process For Receive Filter With A Given Spacecraft Transmitter Filter

Optimization Process

- Compute time domain response of the complete system.
- Compute the noise bandwidth of the receive system.
- Iterate receive system pole and zero locations until time domain response looks promising with respect to ISI and receive noise bandwidth is near the ideal value.
- Then generate eye diagrams.
- Calculate the error rate of a given pattern and average over multiple patterns for different 10log Eb/No's.
- Repeat process until performance is optimized.

LEO Image Satellites

- For all LEO image type satellites with transmit filtering for emission control and perhaps transmission of multiple channels optimizing the pole-zero locations in the receive matched filter can greatly improve performance. (e.g., 3 or 4 dB from theory to < 1 dB from theory)
- NOTE: Receive equipment is usually sold off against Wideband Test Modulator so performance with nonoptimized receive filter may look excellent but be much worse with the actual satellite.
- We perform this optimization for all satellites.

- Center frequency 8.33GHz bit rate 80 Mb/s
- Deep Space Band starts at 8.4GHz
- Power limited so can't use Nyquist filtering because of X/sin X compensation.
- Use sharp cutoff elliptic transmit filtering to meet DSN requirements.
- Optimize receive filter with the transmit filter
- Performance with the satellite filter is the same as without.

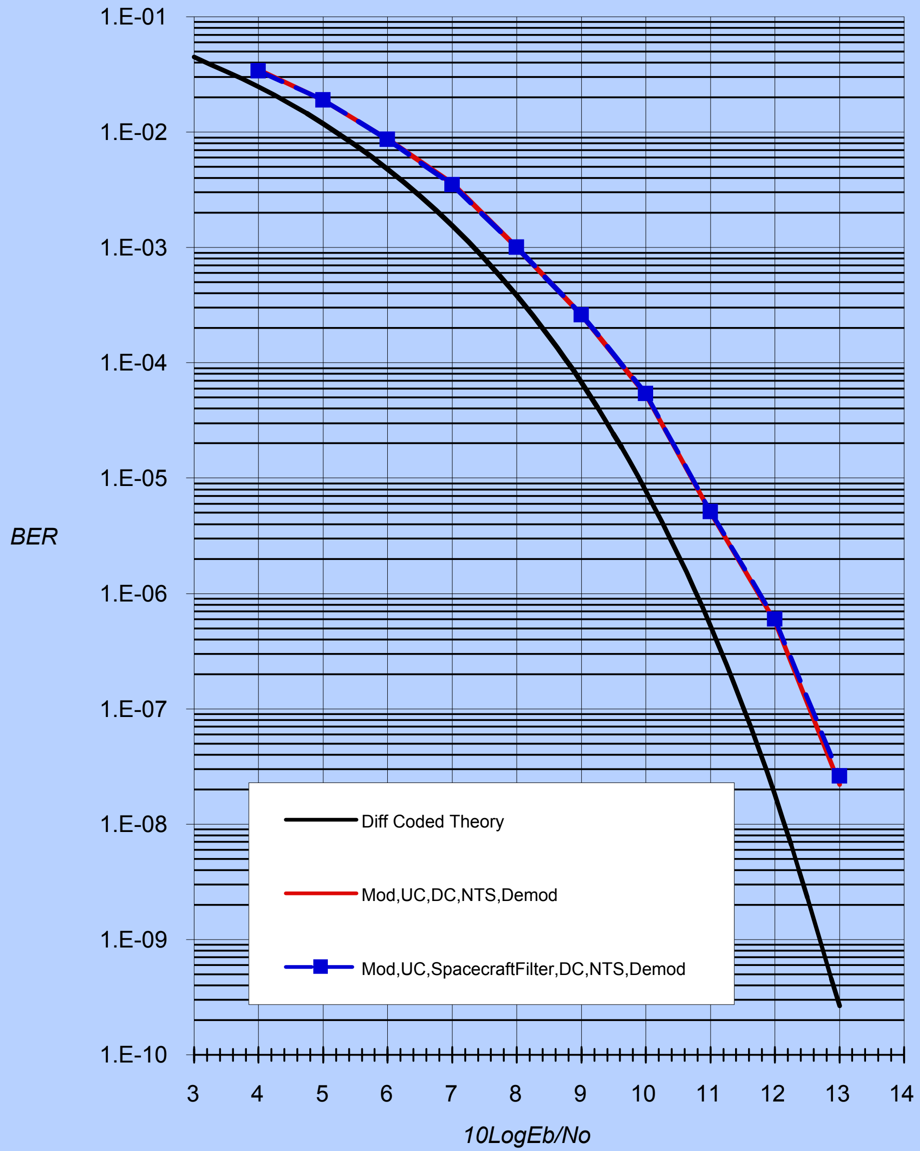


Figure 4. Calipso Satellite BER Curves

How can we change the satellite transmitter topology and filtering so that we simultaneously achieve the desired emission control while achieving excellent BER performance?

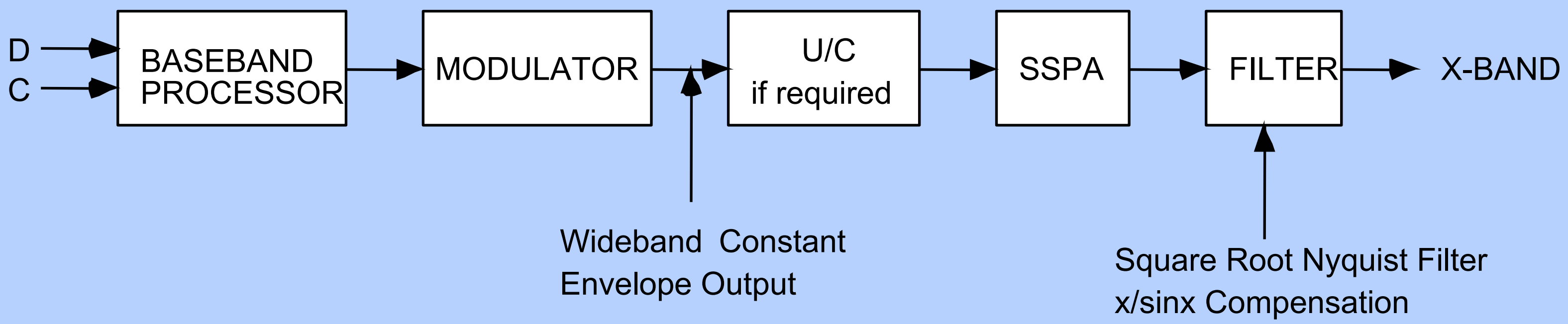
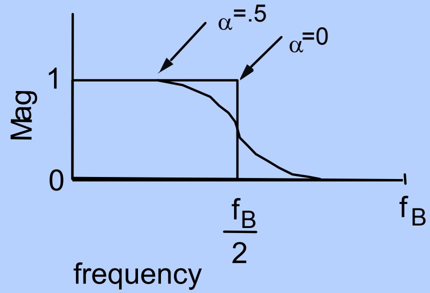


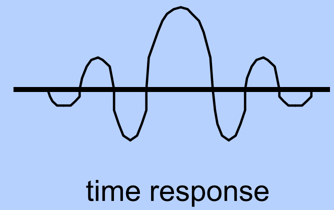
Figure 5. Preferred Transmitter Topology

Advantages Of The Preferred Topology And Filtering

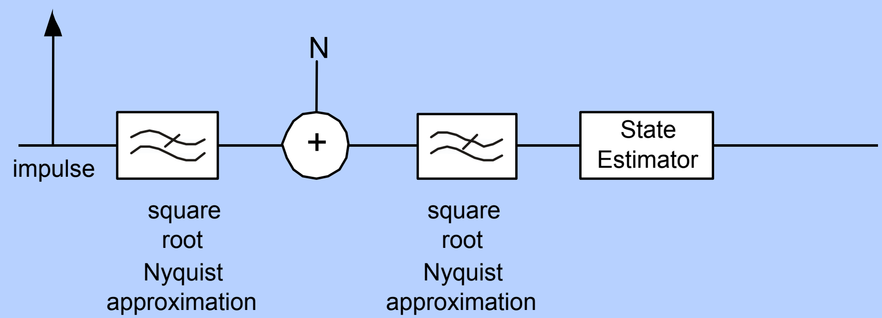
- Wideband modulator and upconverter with constant envelope outputs.
- SSPA is also wideband.
- With constant envelope input SSPA AM/AM and AM/PM are minimized.
- No sideband restoration issues with SSPA.
- Output filter is square root Nyquist filter with X /sin X compensation. This filter in conjunction with the receive square root Nyquist filter yields excellent BER performance.
- Transmit filter design is such that the requirements of the DSN are met.

NYQUIST FILTER





COMM. LINK WITH WHITE GAUSSIAN NOISE



ACTUAL COMM. LINK USES RECTANGULAR PULSES

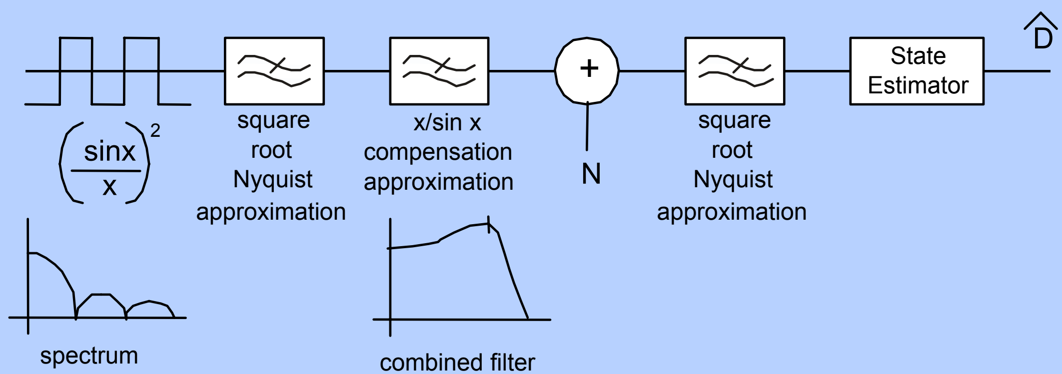


Figure 6. Nyquist Filtering

Actual Coded Satellite Link at 8.2 GHz with 280 Mb/s Information Rate and 320 Mb/s OQPSK Transmit Rate

What are the filtering requirements imposed by the DSN?

-140 dBW / m^2 / 4KHz per ITU at the surface of the earth

-36 dB 10log 4 x 10^3

Implies -176 dBW / m^2 / Hz for the signal

-13.47 dB first sidelobe peak

Implies -189.47 dBW / m^2 / Hz at 8.44 GHz in the deep space band

CCIR 578 - Max -220 dBW / Hz into receiver at DSN site

Conservative effective antenna area for 70m antenna at DSN is 35.85 dB

Implies -255.85 dBW / m^2 / Hz at the surface of the antenna

Thus 66.38 dB attenuation is required by the transmit filter at 8.44 GHz. This is the worst case point in the deep space band.

Assume 66.5 dB attenuation spec for transmit filter across the deep space band.

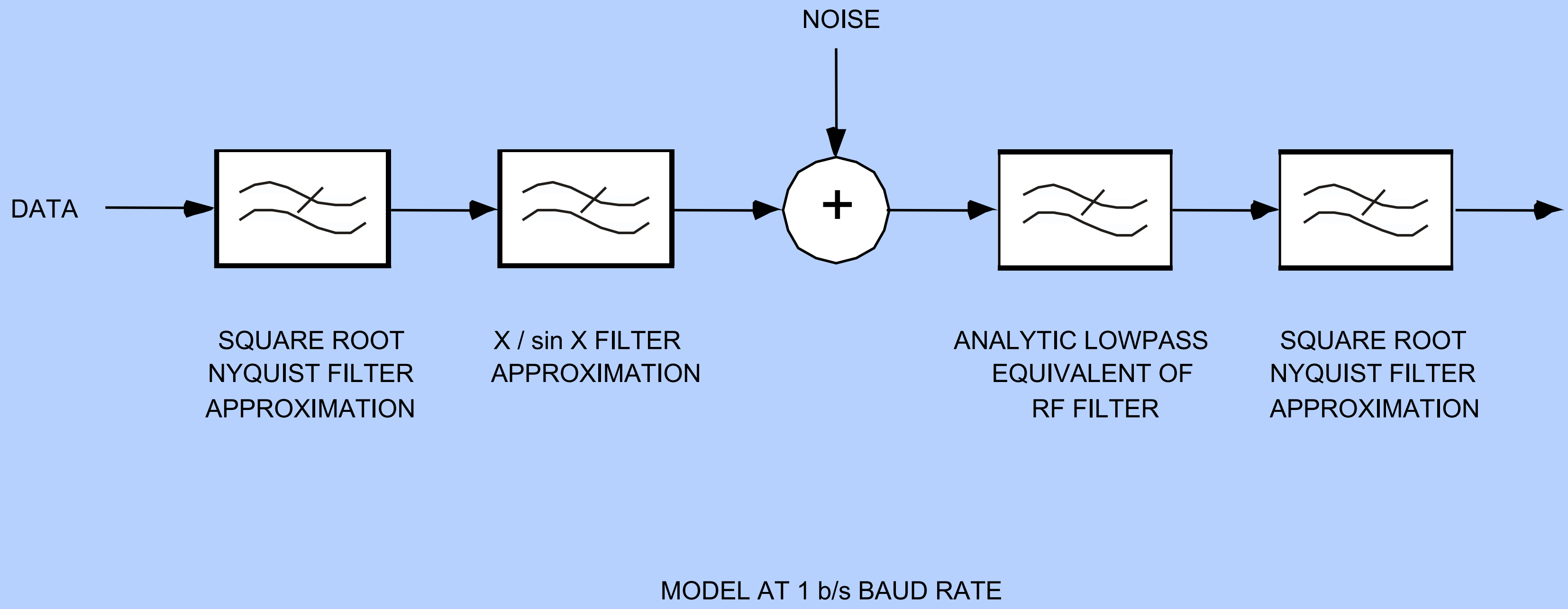


Figure 7. Block Diagram Of Optimization Process For Nyquist Satellite Link

Optimization Process

- Actual square root Nyquist filter frequency response goes to zero in finite bandwidth. This requires infinite number of pole and zeros. Therefore one can only approximate the filter shape.
- Likewise X/sin X goes to infinity at the baud rate frequency. Thus one can only approximate X / sin X over part of the baud rate bandwidth.
- Model any input RF receive filter.
- At 1b/s baud rate choose polynomials in the frequency domain that approximate the desired filter shapes.
- The transmit filter must also meet the scaled frequency requirements of the DSN.
- Calculate time domain response, calculate noise bandwidth of the receive system, generate eye diagrams, and calculate BER performance of candidate filter system.
- Iterate choices until excellent BER is achieved while meeting the requirements of the DSN.

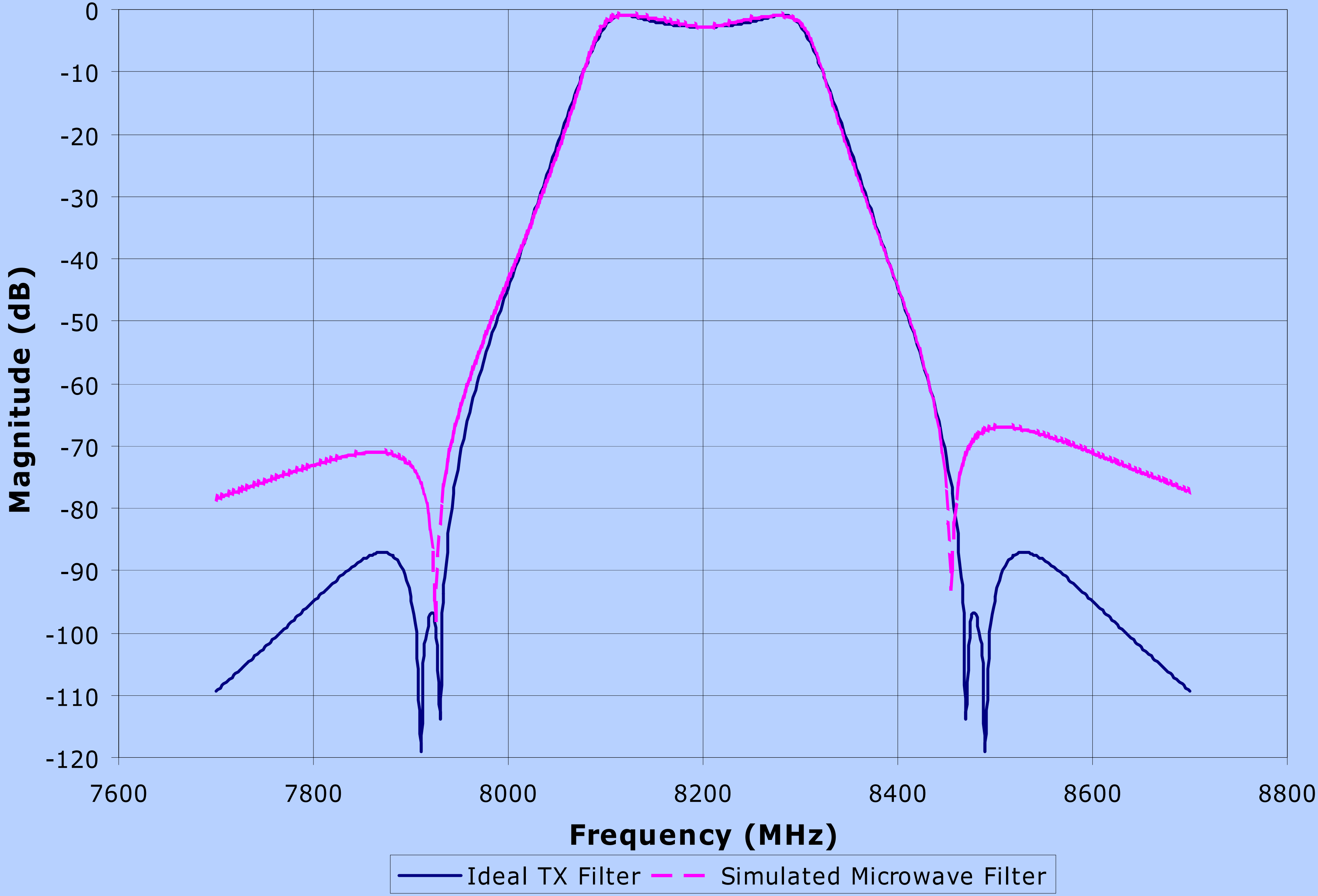


Figure 8. Ideal Transmit Filter vs. Microwave Filter Simulation

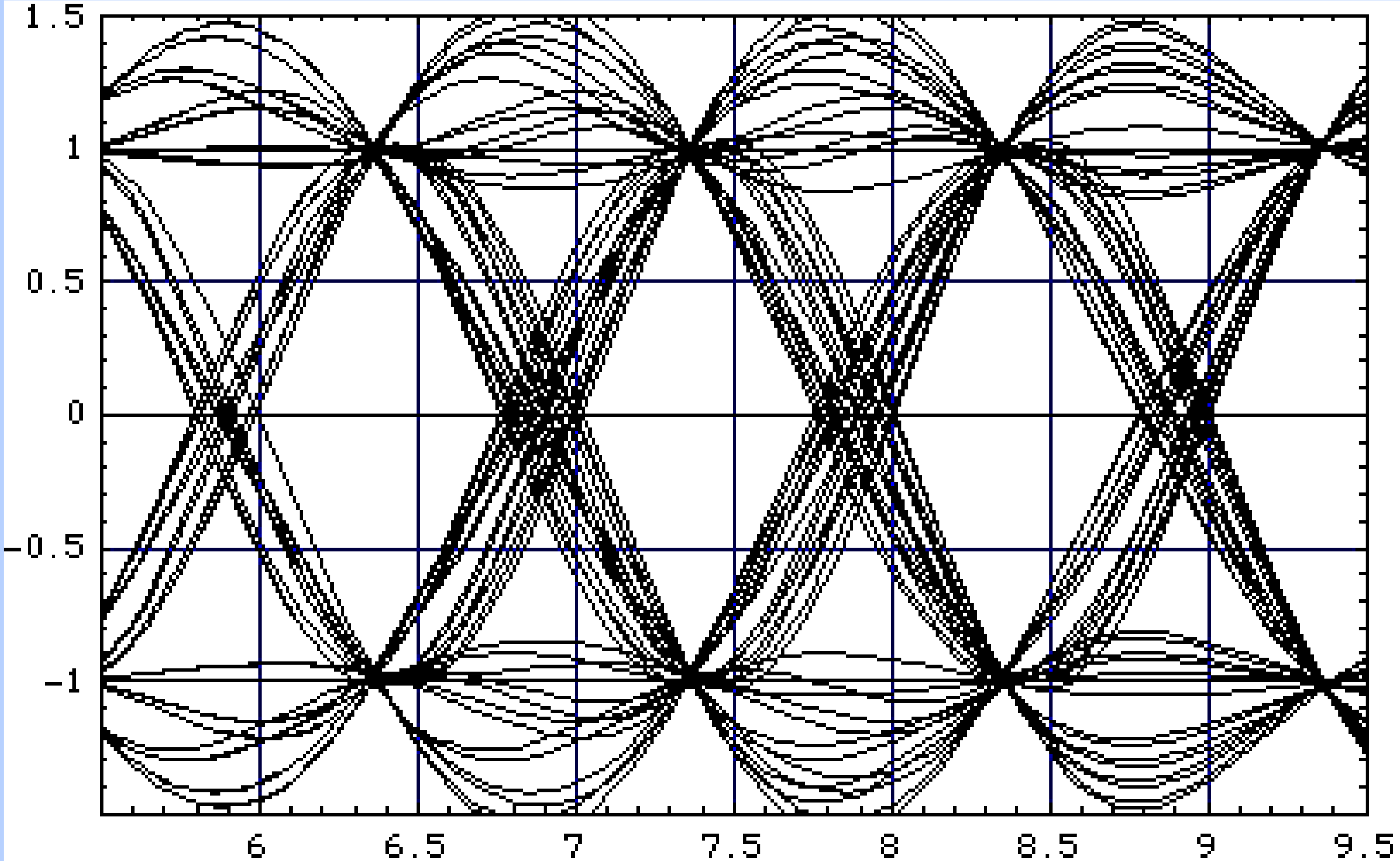


Figure 9. Eye Diagram For The Nyquist System

Predicted Performance For The Nyquist System

10 log Eb / No	Delta From Theory
14	0.510 dB
12	0.468 dB
10	0.439 dB
8	0.416 dB
6	0.384 dB

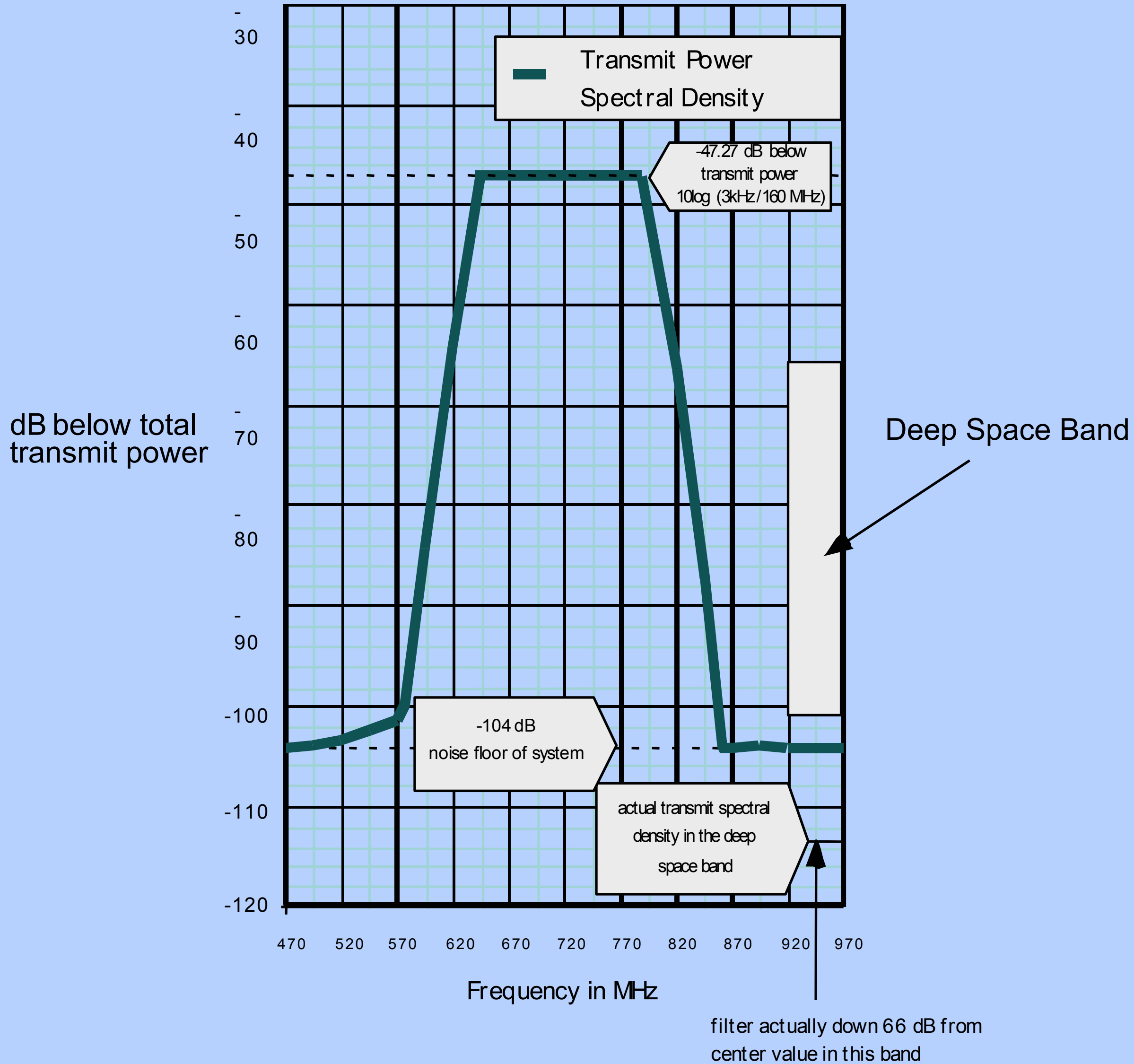


Figure 10. Actual Transmit Power Spectrum of the Nyquist System at 8200 MHz Downconverted to 720 MHz

Red.. Convolutional Encoder, Modulator, Upconverter, Downconverter, Demodulator, FEC Decoder

@ 10^{-9} 1.2dB from theory

Green.. Convolutional Encoder, Modulator, Upconverter,Spacecraft EDU Filter, Downconverter, Demodulator, FEC Decoder

@ 10^{-9} 1.8dB from theory

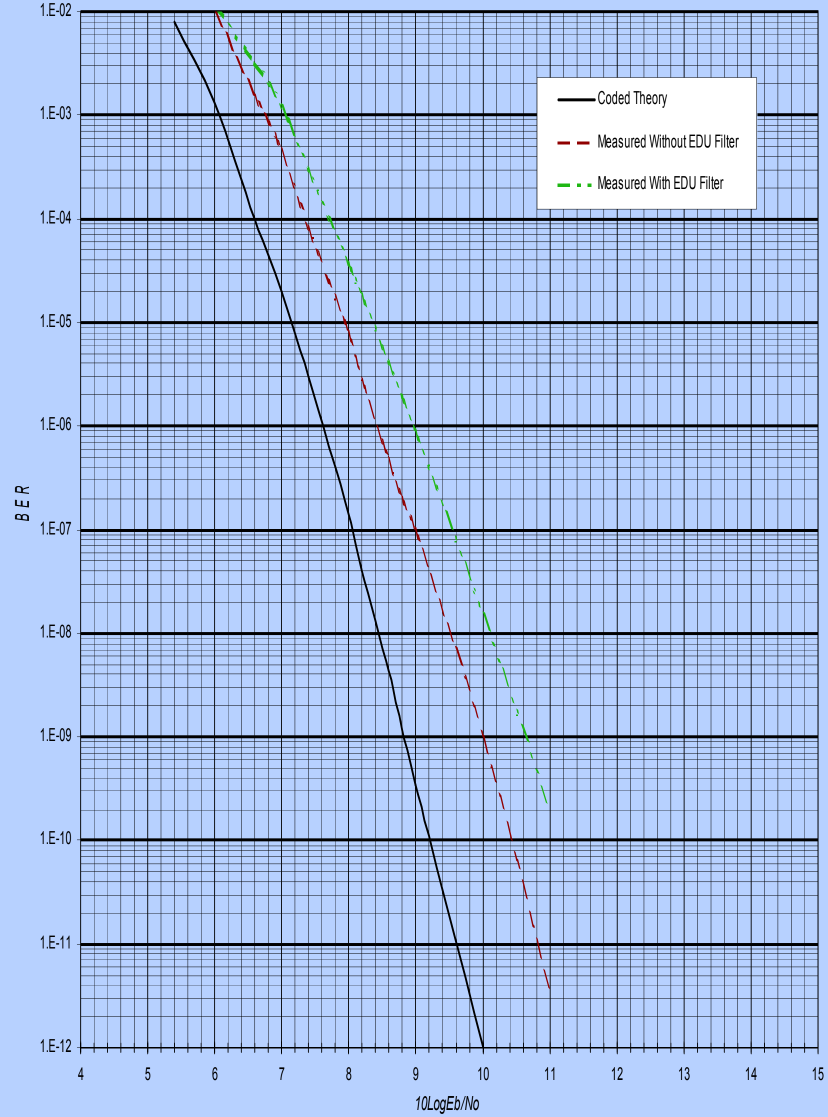


Figure 11. Actual Performance of Coded Nyquist System (280 Mb/s Information Rate 320 Mb/s Transmit Rate)

What is the baud rate limit at X-Band while meeting the DSN emission requirements?

- Since DSN only causes problem on the high side of the spectrum one can offset the center frequency to 8185 MHz instead of the band center at 8212.5 MHz. This yields 27.5 MHz additional frequency for filter roll off.
- Thus the center frequency is 215 MHz from 8400 MHz deep space band lower frequency limit.
- Since the baud rate spectral component is a discrete frequency it should be kept out of the deep space band.
- Likewise, one must allow for a telemetry signal. Place near the null in the wideband spectrum. This allows the wideband and the narrowband signals to co-exist.
- From these considerations multiple system operators have concluded that 200 Mb/s is the maximum baud rate at X-Band as shown in the following figure.

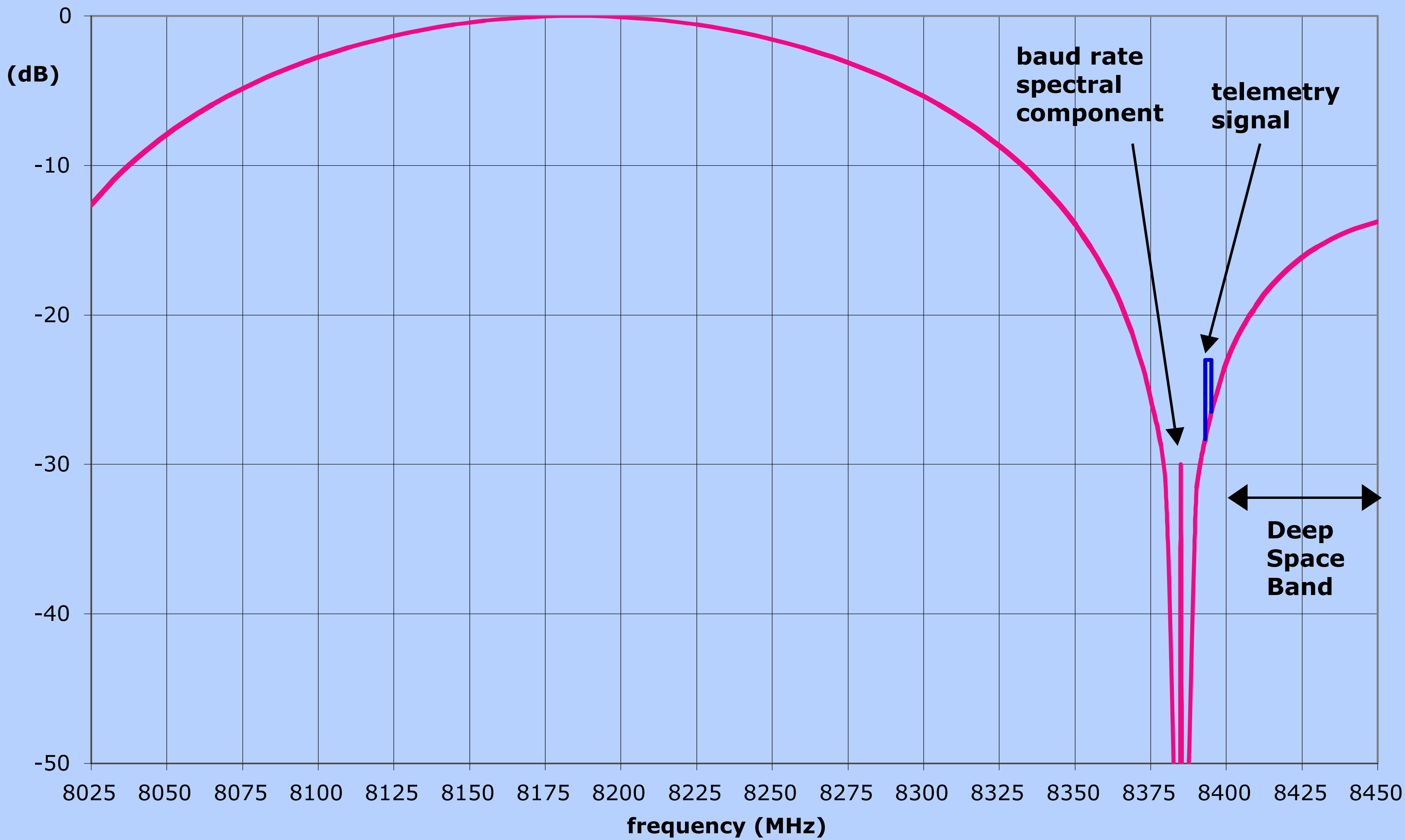


Figure 12. Unfiltered Transmit Spectrum Centered at 8185MHz at 200Mb/s Baud Rate (400Mb/s OQPSK and 600Mb/s 8PSK)

Filtering at 200Mb/s Baud Rate Required to Meet the DSN Requirements

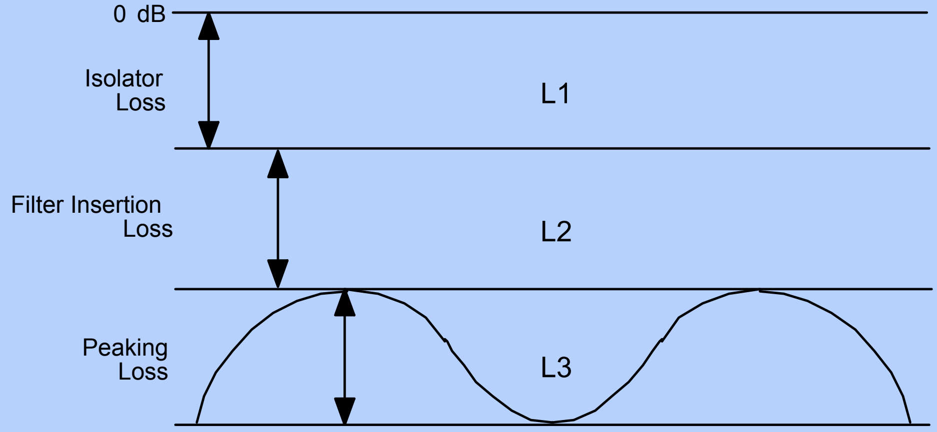
- Using the same type of analysis as previously discussed the results are:

  -176 dBW / m^2 / Hz signal at surface of the earth

  -255.85 dBW / m^2 /Hz allowed at surface of the earth from 8400 - 8450 Hz

- Taking into account the (sin X / X)^2 roll off of the signal the following results are found.

Frequency MHz	10log[sin X/X]^2	Required Filter Loss
8400	-23.207 dB	56.646 dB
8410	-19.309 dB	60.544 dB
8420	-16.982 dB	62.870 dB
8430	-15.455 dB	64.398 dB
8440	-14.432 dB	64.421 dB
8450	-13.772 dB	66.801 dB

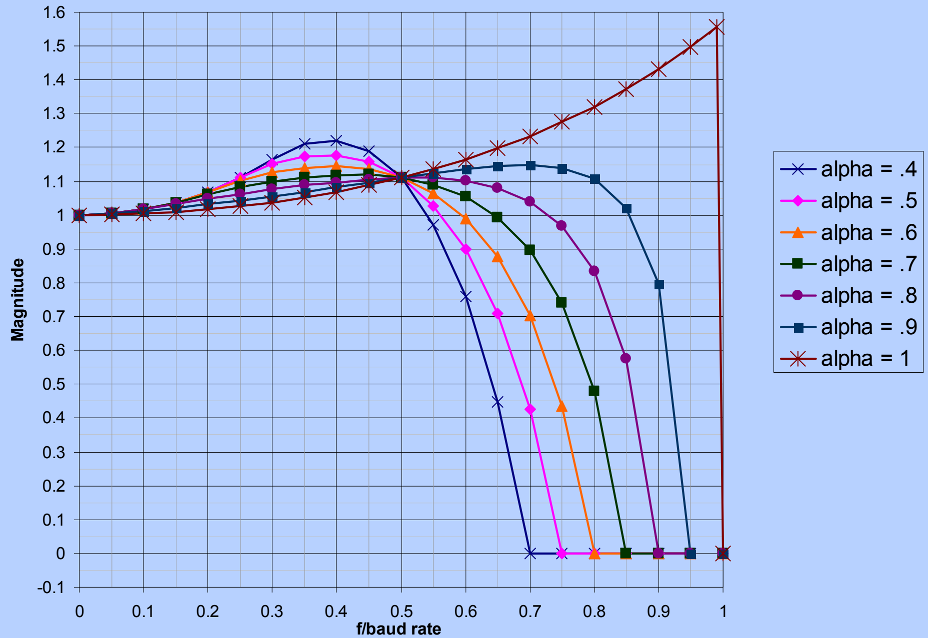


POUT = PIN – L0 – L1 – L2 – L3

L0 is loss in dB of passing $(\sin x/x)^2$ data spectrum through filter shape.
L1 is loss of any isolators on the input and output of the filter. Excellent source and load return loss is required for precision filtering.
L2 is actual insertion loss of filter from its peak.
L3 is peaking loss of the filter. Peaking can only be achieved by additional loss in center.
PIN is the power at the output of the SSPA.

Would like to maximize transmitter power by minimizing the peaking loss of the filter caused by X / sin X compensation. Let's look at X / sin X times Root Raised Cosine Nyquist filter.

Figure 13. Transmitter Output Power



Smaller alpha filters with X / sin X correction have greater peaking but roll off earlier. Greater peaking results in more filter loss (with passive filter one can only achieve peaking by greater loss at DC) but makes it easier to meet the stop band.

For a value of alpha = 0.7 to 0.8 the filter peaking is minimum at about 0.9 dB. This results in less filter loss, but a greater alpha requires faster roll off and thus a higher order practical filter.

In the alpha = 0.9 to 1.0 region, peaking again increases while roll off must be even sharper. Therefore, this is an undesirable region.

Figure 14. X / sin X Times Root Raised Cosine Filter

From the previous, it is seen that filter loss due to peaking can be minimized if one uses an alpha in the 0.7 to 0.8 range. Therefore an approximation to the alpha = 0.7 ideal filter with x/sinx compensation was investigated. This resulted in the following filter.

- a = 0.7 root raised cosine approximation with x/sinx compensation so that peaking of filter is minimum. This minimizes power loss through the transmit filter.
- analytic low pass filter approximation is twelve pole, seven zero filter
- peaking 0.91 dB maximum

L0 loss due to passing $(\sin x/x)^2$ spectrum through filter shape is only 0.246 dB

The normalized stopband filter response is plotted below. This can be converted to actual delta frequencies from the center frequency by multiplying abscissa points by 200 MHz.

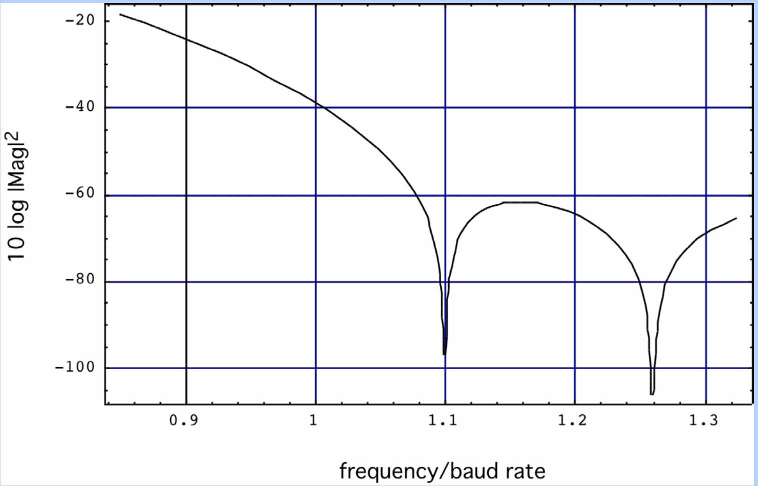


Figure 15. Transmit Filter Response

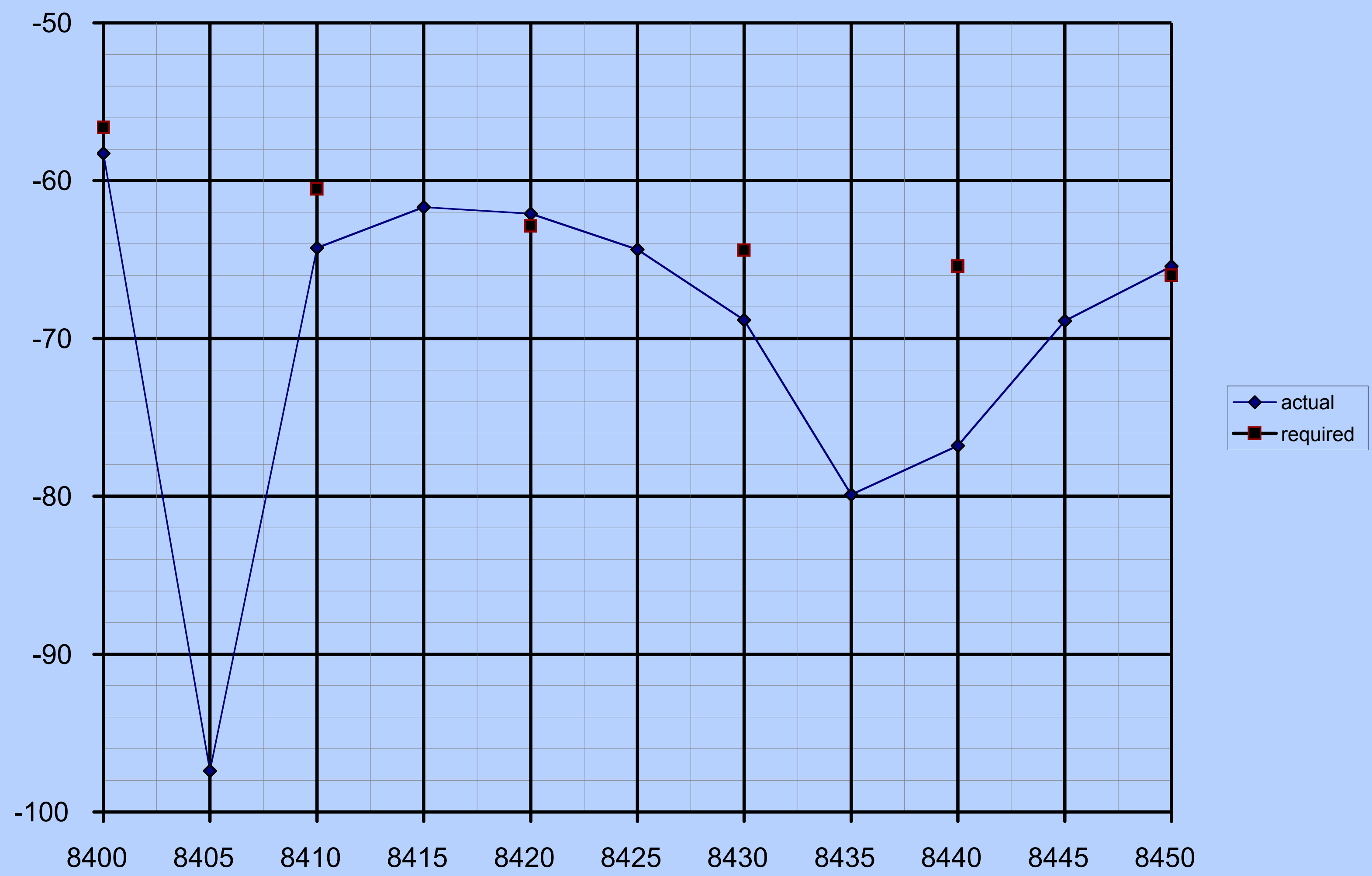


Figure 16. Transmit Filter Response In The Deep Space Band

- The receive filter is designed to optimize performance with the proposed TX filter.
- The analytic low pass filter approximation is an eight pole, two zero filter.
- The eye diagram at the output of the receive filter for random data passed through both the transmit and receive filter is plotted below. One can see that the eye is very open and clean looking.

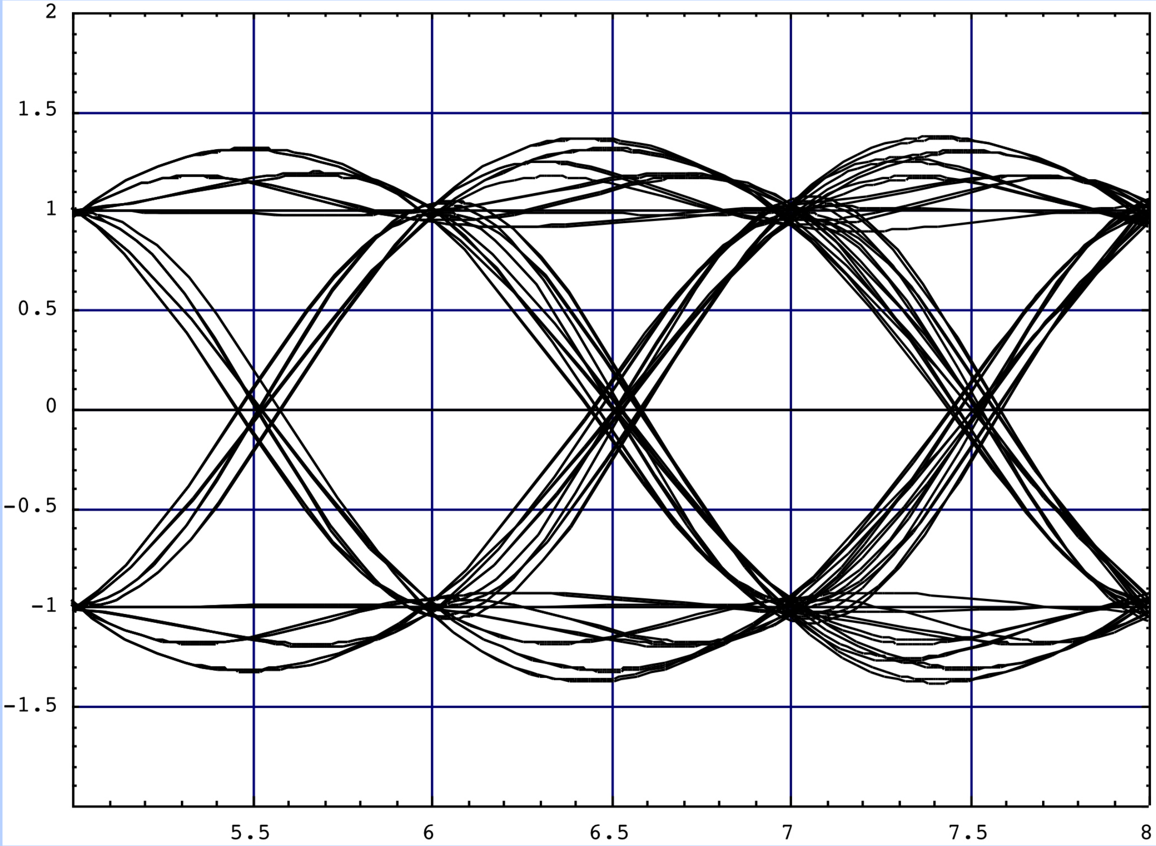


Figure 17. Receive Filter and System Eye Diagram

Predicted Performance For The 200 Mb/s Baud Rate System At X-Band

10 log Eb / No	Delta From Theory
14	0.680 dB
12	0.583 dB
10	0.498 dB
8	0.431 dB
6	0.368 dB

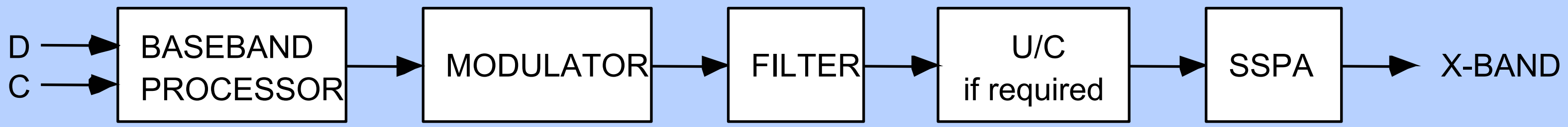
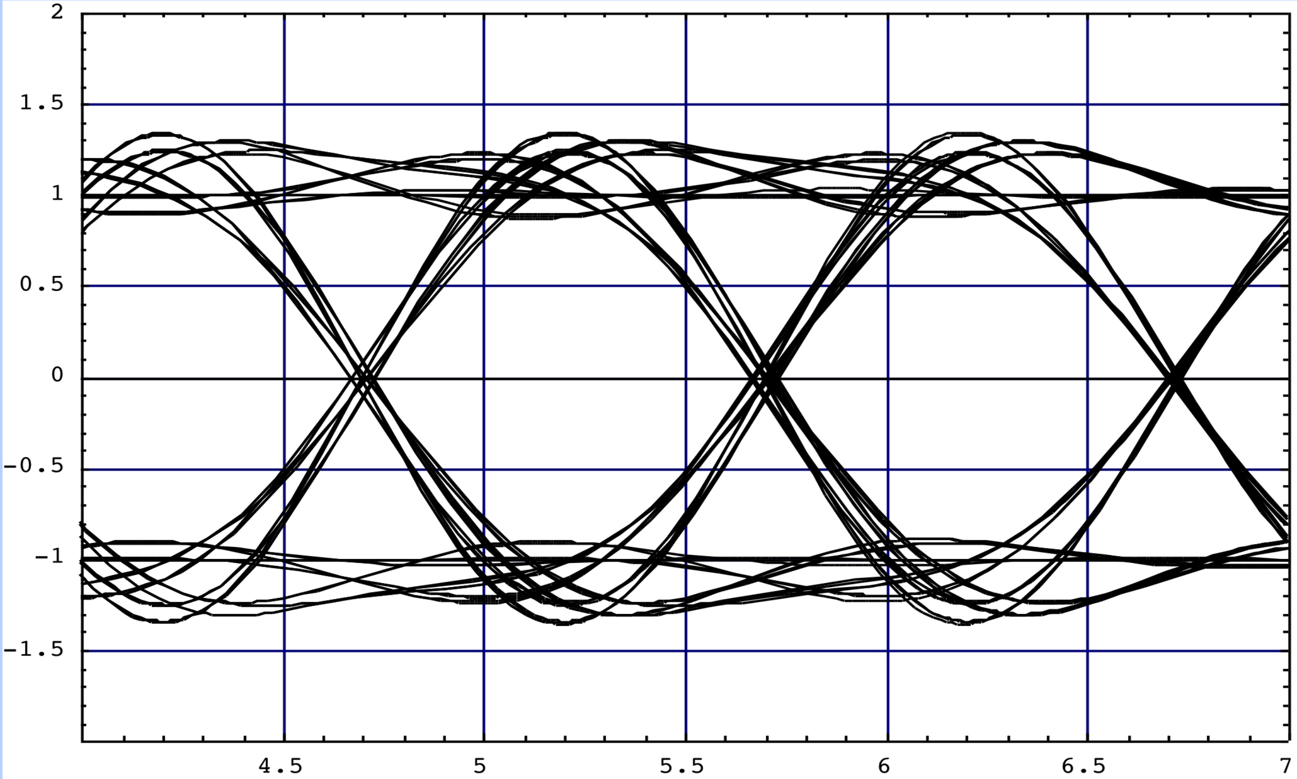


Figure 18. Alternate Transmitter Topology



The eye diagram of the signal with transmit filtering shows that the signal peak is 1.33 times the unfiltered signal peak.

Thus peak power ability of amplifier must be 20 log 1.333 or 2.5 dB above average output power. Thus P_{1dB} of the SSPA must be somewhat greater than 2.5 dB above average power out for linear operation. For example with 1 dB output backoff for linear operation the P_{1dB} of the SSPA would be 3.5 dB above the desired average output power level.

Figure 19. Effect of The Modulator Filtering On The Time Domain Response

Preferred Topology vs. Alternate Topology

Comparison of the preferred topology SSPA output power requirement versus the alternate topology SSPA output power requirement for a given output power from the transmitter reveals that the two power requirements are almost identical. The preferred topology is much less dependent upon the SSPA linearity in meeting emission requirements.